

LOW REYNOLDS NUMBER DROPLET COMBUSTION IN CO₂ ENRICHED ATMOSPHERES IN MICROGRAVITY

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INTRODUCTION

The effect of radiative feedback from the gas phase in micro-gravity combustion processes has been of increasing concern because of the implications in the selection and evaluation of appropriate fire suppressants. The use of CO₂, an optically thick gas in the infrared region of the electromagnetic spectrum, has garnered widespread acceptance as an effective fire suppressant for most ground based applications. Since buoyant forces often dominate the flow field in 1-g environments the temperature field between the flame front and the fuel surface is not significantly affected by gas phase radiative absorption and re-emission as these hot gases are quickly swept downstream. However, in reduced gravity environments where buoyant-driven convective flows are negligible and where low-speed forced convective flows may be present at levels where gas phase radiation becomes important, then changes in environment that enhance gas phase radiative effects need to be better understood. This is particularly true in assessments of flammability limits and selection of appropriate fire suppressants for future space applications. In recognition of this, a ground-based investigation has been established that uses a droplet combustion configuration to systematically study the effects of enhanced gas phase radiation on droplet burn rates, flame structure, and radiative output from the flame zone.

BACKGROUND

It appears that the radiative feedback effects of CO₂, as well as other potential fire suppressants, have been largely un-quantified in the selection and ranking of fire suppressants for spacecraft fires. Since the extinction mechanism of many micro-gravity flames is radiation dominated it is reasonable to expect that the emissive and absorptive properties of the surrounding gases would play a role. Mention of the radiative interplay between flame and surroundings was made in discussing ranking criteria of fire suppressants in an earlier work; however, it was then reasoned that CO₂, for the very reasons that this suppressant may be problematic in micro-gravity, should be ranked the highest. The paper stated:

*“For a suppressant to be effective radiatively, it must decrease flame luminosity, act as a radiation sink itself, and **remain transparent between the flame and its surroundings**. On this basis CO₂ was favored because CO₂ decreases sooting in diffusion flames by 20-30 percent more than does N₂ and CO₂ is more active radiatively (infrared) than N₂.” [1]*

It has not been established that CO₂ is “transparent” in the distances, temperatures, and concentrations which may come into play in the event of a release in the *International Space Station*. Additionally, it is not clear that consideration was made of the possibility that radiative

emissions from heated gases, following a substantial fire, could potentially serve more as a radiative “source” rather than a radiative “sink” with respect to the fuel surface.

Recent work has highlighted this concern and is, in part, the focus of a current investigation funded under an NRA’99 solicitation. There, it was proposed to experimentally assess the efficacy of CO₂ as a fire suppressant in space environments by observing extinguishment characteristics of a burning PMMA test sample using various blends of CO₂/Air. This work is, in part, motivated by the recognized need to provide a better understanding of the radiative effects of CO₂ as stated in the following excerpt from the investigation’s proposal listing concerns with fire suppression practices and policies in space:

“Carbon Dioxide, the suppressant of choice for ISS, behaves differently than other diluent, in regard to its impact on the range of oxygen concentrations that will support a flame. Whereas the range of flammable conditions narrows substantially in quiescent microgravity as compared to normal gravity for most diluent, the range is unaffected when carbon dioxide replaces nitrogen [Honda and Ronney 1997]. This is due to the fact that carbon dioxide absorbs radiation from a flame more readily than nitrogen, helium, or argon. Thus, the additional margin itself is absent in atmospheres diluted with carbon dioxide.” [2]

This work will provide a means of quantifying the effects of an enriched CO₂ environment through measurements of the changes in droplet burn rates, flame structure, and radiative losses. The droplet, in this case, serves as a proxy for a burning fuel particle and should provide a reasonable index of the concerns associated with fires surrounded by participating gases without the added complexities typical in many solid fuel experiments (e.g., changes in surface geometries, changes in surface emissivities, temperature dependencies, poorly characterized burn rates, etc.). Measurements of droplet burn rates and flame structure will subsequently be used in a 2-D axisymmetric numerical model, incorporating gas phase radiation, to further refine the distinctions between radiative heating and other changes in transport phenomena due to changes in CO₂ concentrations.

Use of a droplet test configuration is advantageous in two ways; first, a wealth of experimental data on droplet burn rates and flame structure already exists and this will serve as a convenient baseline for comparison. Secondly, the axisymmetric geometry of a droplet burning in a flow field lends itself to numerical modeling and subsequent verification more readily than other geometries.

SCIENTIFIC OBJECTIVES

The primary motivation behind this research is to provide an easily quantifiable and repeatable measure of the effectiveness of CO₂ as a space based fire suppressant. Previous work with radiatively participating gases indicate that high CO₂ concentrations in oxidizing environments may result in broader flammability limits due to radiative feedback to the fuel source and absorption in the surrounding gas phase combined with a lack of buoyant forces that normally minimize this effect in normal gravity environments [3,4]. A secondary motivation is to provide a database from tests performed in μg that will provide well-defined “test cases” to be used in the validation of droplet models that include gas phase radiation phenomena.

As such, this investigation will provide a test configuration that will allow indirect measurement of the gas phase radiative effects of a CO₂ enriched environment. This is accomplished by measuring variations in burn rates and flame structure of large fuel droplets (i.e., approaching 2.5 mm in diameter) in an environment with varying levels of CO₂ concentration. Additionally, because of the droplet's relatively simple axisymmetric geometry it is expected that an accurate correlation can be made with a 2-D axisymmetric droplet model in low speed flows that incorporate gas phase radiation. The model, once validated with the experimental results, will subsequently be used to provide predictions of the effects of gas phase radiation in enriched CO₂ environments for larger scale geometries and boundary conditions more representative of existing space habitats relying on CO₂ fire suppressants.

Two overarching science objectives are stated as follows:

- Measure the effect that an enriched CO₂ environment has on the burn rate and flame structure of a liquid droplet in a low convective environment by performing tests at various CO₂/Air mixture levels for a range of pressures and temperatures in both 1-g and micro-gravity.
- Develop a 2-dimensional numerical model of a burning droplet with a sufficiently detailed gas phase radiation model and use the experimental results to validate the model.

EXPERIMENTAL APPROACH

The first objective will be accomplished through a series of tests using two fuel types; a non-sooting fuel such as methanol and a sooting fuel such as n-heptane. A benchmark data base will initially be established in dry air (i.e., 21% O₂ and the balance N₂) at 1-g and 0-g in a quiescent environment at 25°C. Initial fuel droplet sizes will be approximately 2.5 mm in diameter and the burn rate will be precisely measured from recorded backlit images of the droplet. Two radiometers, a wide band and a narrow band (set to capture the predominant water line) will be used to obtain comparative information on the flame's intensity. The flame temperature will be measured by insertion of a thermocouple or by thin-filament pyrometry.

During the first phase of testing the combustion environment will be altered between tests by changing the ambient pressure from 1 atm to 3 atm. The increased pressure will effectively increase the optical thickness of the gases and will allow test chamber results to be extrapolated to geometries involving greater distances in 1 atm environments, such as may be evident in the *International Space Station*.

The second phase of testing will use a translating device (i.e., previously designed and built for use in ground testing performed for an on-going flight investigation¹ [5]; refer to Figure 1) to move the burning droplet at a precisely controlled speed (i.e., 5 cm/sec). The desire for a relative velocity between the oxidizer and droplet is to provide a test configuration that replicates a more likely combustion environment. On the *International Space Station* air flow behind the

¹ Flight investigation entitled “*Dynamics of Droplet Combustion and Extinction in Slow Convective Flows*” and directed by Vedha Nayagam (i.e., Principal Investigator).

experimental racks and in ventilation ducting is designed to be less than 20 cm/sec. Using this test configuration will provide an axisymmetric flame geometry and will establish a basis for relative comparisons of the combined convective and radiative heating effects. It is expected that due to the alteration of the inner region's temperature field resulting from the presence of the radiatively participating gases the convective heating effects will be greater than that observed without the radiatively participating gases.

The third and final phase of testing will be conducted at elevated ambient temperatures of 80°C (or higher if practicable). It is expected that the thermal effects of the gas phase radiation will increase with CO₂ concentration and with ambient temperature resulting in measurable differences in the droplet burn rates, flame stand-off distances, and the flame's radiative intensity. Further, it is expected that the radiative feedback effect will be more pronounced with the non-sooting fuel since the presence of a soot shell (e.g., with n-heptane droplets), which typically forms around the droplet in quiescent environments or in low convective flows, already functions as a radiative medium in the inner region between the flame and the droplet.

ACKNOWLEDGEMENT

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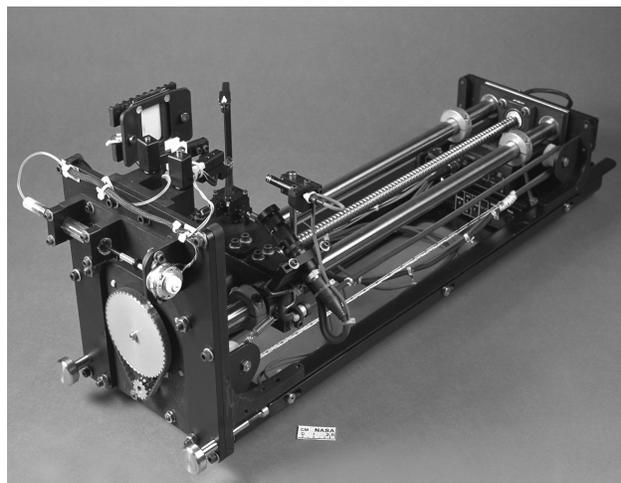


Figure 1(a) Translating sub-assembly designed for the "Dynamics of Droplet Combustion and Extinction in Slow Convective Flows" flight investigation led by Vedha Nayagam (i.e., Principal Investigator) for use in the Zero Gravity Facility (i.e., "5 Second Tower").

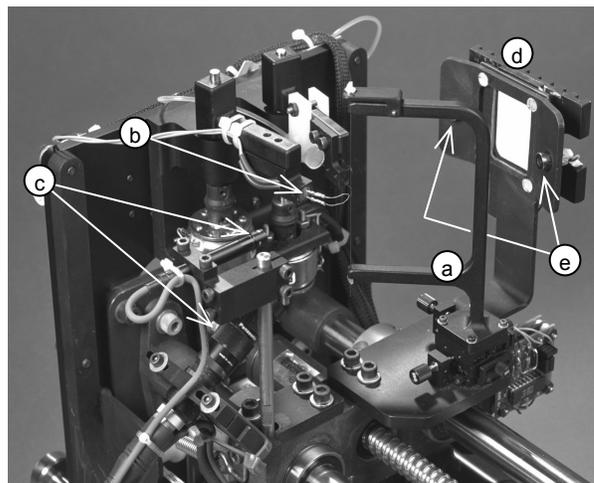


Figure 1(b) Close-up of the "translating subassembly" showing the (a) fiber support fixture, (b) ignitor wire, (c) remote camera heads, (d) LED backlight panel, and (e) radiometer locations.